The origin of transparent and non-transparent white pumice: A case study of the 52ka Maninjau caldera forming eruption, Indonesia

Indranova Suhendro[1], Atsushi Toramaru[1], Agung Harijoko[2,3], Haryo Edi Wibowo[2,3]

[1]Department of Earth and Planetary Sciences, Graduate School of Science, Kyushu University, Nishiku, 744, Motooka, Fukuoka, 819-0395, Japan

[2]Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika no.2, Yogyakarta, Indonesia

[3]Centre for Disaster Studies, Universitas Gadjah Mada, Jl. Mahoni C-16, Bulaksumur, Yogyakarta, Indonesia

Corresponding author: Indranova Suhendro (indranovasuhendro10@gmail.com)

ABSTRACT

The 52ka eruption of Maninjau caldera produced two distinctive type of white pumices: transparent (TWP) and non-transparent (NTWP). Both pumice types are crystal-poor (avg. 3.3 %), having similar mineralogy (pl>qz>bt>px>opq), similar glass compositions (avg. 78.5 wt. % SiO_2), and similar plagioclase core compositions (avg. An_{20-30}). We found that the abundance of TWP decrease towards the upper stratigraphic positions, together with the increase in NTWP, grey pumice, banded pumice, and lithic contents. Vesicles in TWP are typically dominated by large vesicles, while NTWP is characterized by abundant-small vesicles. Large vesicle corresponds to the preexisting bubble which formed in magma chamber (pheno-bubble, > 0.1 mm). On the other hand, small vesicle in groundmass (matrix-bubble, <0.1 mm) is attributed to second nucleation in the conduit during the eruption. We performed quantitative comparison using pheno- and matrix-bubble number densities (PBND and MBND) for these two white pumice types. The correlation between PBND and MBND result in two regimes: (1) decompression-controlled regime, showing nearly constant-PBND correlation for TWP, and (2) phenobubble-controlled regime, showing steeply-decreasing PBND correlation for NTWP. In the first regime, MBNDs value varies dramatically, suggesting the variation of decompression rate by two to three orders of magnitudes. While in the second regime, the slight increase of MBNDs is considered as the effect of the decrease in PBND within the nearly constant decompression rate.

***Keywords**:* Maninjau; transparent white pumice; pheno-bubble; matrix-bubble; bubble number density

INTRODUCTION

Bubbles in pyroclasts is believed to record the physical state and vesiculation history of magma, either in magma chamber and conduit (Toramaru 2006, 2014; Shea 2017; Edmonds and Woods 2018). Such vesiculation process in magma chamber, which occurs via heterogeneous nucleation in cooling-crystallization (second boiling) is represented by pre-eruptive bubbles and named as pheno-bubble (Toramaru, 2014). On the other hand, the vesiculation in conduit, which occurs homogeneous nucleation (or often called second nucleation in magmas with pre-eruptive bubbles) under decompression, is recorded by syn-eruptive bubbles and defined as matrix-bubble (Toramaru, 2014). This introduction of pheno- and matrix-bubbles thus become essential to advance the understanding of eruption dynamics, not only because pheno-bubbles provides buoyancy and/or overpressure in magma chamber (thus triggers an eruption), but also controls second nucleation under decompression during the eruption. Particularly, high pheno-bubble number density magmas will limit the second nucleation because supersaturation is effectively diminished by the overgrowth of pheno-bubbles (Toramaru, 2014). Hence, higher magma decompression rate is needed in order to generate second nucleation in high pheno-bubble number density magmas. By applying this idea to natural samples, it has been demonstrated that pyroclasts from any reported explosive volcanic eruptions are containing abundant small vesicles with high matrix-bubble number density values (suggesting that the magma experience with high decompression rate and the number density of pheno-bubbles does not significantly limit the supersaturation of matrix-bubbles) and apparently not transparent.

Interestingly, we found that the VEI-7 (220-250 km^3 erupted volume) and 52ka eruption of Maninjau caldera in West Sumatra, Indonesia (Purbo-Hadiwidjoyo et al.1979; Alloway et al. 2004) (Fig. 1A), produced an unusual white pumice type that we call transparent pumice (TWP), which lacks matrix-bubble and mainly includes pheno-bubbles, together with the common white pumice type that we call non-transparent pumice (NTWP) that includes dense population of matrix-bubbles and lacks pheno-bubble (Fig. 2A). This leaves an important question: what factor controls the formation of TWP and NTWP within the same eruption?

In this paper, we present a novel correlation between pheno- and matrix-bubble number densities, combined with detailed componentry, petrography, compositional analysis, and textural analysis of TWP and NTWP. Finally, based on these results, we argue that the transitions between TWP and NTWP strongly depends on the intensity of matrix-bubble nucleation that controlled by magma decompression rate and the abundance of pheno-bubble in erupted magma.

MANINJAU CALDERA, INDONESIA

Maninjau caldera is one of the largest calderas in Indonesia (220-250 km^3 erupted volume; Purbo-Hadiwidjoyo et al. 1979) that situated in Sumatra Island, above the subduction zone between Eurasian and Indo-Australian plates (Fig. 1A). The 52ka eruption of Maninjau produced non-welded ignimbrite without any Plinian fall deposits. Alloway et al. (2004) described that the lowermost ignimbrite is characterized by the abundant basal surge layer and gas pipe structure that underlined by the thick and massive ignimbrite. The eruption age 52 ±3 ka was obtained from ^{14}C dating for southwestern and eastern ignimbrite deposits (Alloway et al. 2004). Some previous studies have shown that Maninjau pre-caldera lavas span from basaltic andesite to andesite (55 – 60 wt. % SiO_2), while the 52ka ignimbrite reaches up to rhyolitic composition (74 – 77 wt. % SiO_2) (Harahap and Abidin, 2006; Leo et al. 1980; de Maisonneuve and Bergal-Kulvikas, 2020).

METHODS

Sampling and component analysis

We selected 11 observation locations with focus to collect samples from all ignimbrite directions, including northern, eastern, western, and southern deposits (Fig. 1B). All deposits are categorized as non-welded ignimbrites. The collected samples were sieved using -5φ (>32 mm) to 1φ (<1/2 mm) sieves. Next, we qualitatively observe and quantitatively count the grains from -5φ (>32 mm) to -1φ (2-4 mm) mesh size in order to identify the main component types.

Bulk density

1094 white pumice grains (713 for TWP and 381 for NTWP) with 4-16 mm size from all ignimbrite directions were selected for bulk density analysis. First, we measure the weight using electronic mass balancer. Afterwards, pumice grains were scanned by MEDIT-3D Laser scanner (manufactured by Sea Force Company) and processed by HIRA 3D view software at the Petrology and Volcanology Laboratory, Kyushu University in order to get the 3D surface image and bulk volume of pumice grain. Finally, bulk density can be obtained from simple equation as follow:

$$\rho = m/v \tag{1}$$

where ρ is bulk density in gr/cm^3, m is mass of the grain in gram (gr), and v is volume of the grain in cm^3.

Petrography, glass, and plagioclase compositions

84 thin sections of white pumice (45 TWP, 39 NTWP) from 4-16 mm size were observed by optical microscope, including the lowest to the highest bulk density value. Samples containing elongated bubble were cut perpendicular to the elongation direction. Mosaic images for each thin section were taken by using HITACHI TN3030 Plus Miniscope Scanning Electron Microscope (SEM) at the Petrology and Volcanology Laboratory, Kyushu University. Major elements in glass and 43 plagioclase phenocrysts were analyzed by utilizing JEOL JXA 8530-F Field Emission Electron Microprobe at the Faculty of Science, Kyushu University, using a focused beam with 1μm diameter size and 15 kV accelerating voltage.

Bubble size distribution (BSD)

200x image magnification was chosen as it is capable to identify the smallest size of pheno-bubble and largest size of matrix-bubble. Next, we digitize the observed vesicles and make corrections for coalesced bubbles by manually separating the vesicle bodies (Fig. 3S in the supplemental data). Correcting each bubble morphologies from bubble coalescence is highly important in order to represent the actual distribution value of the bubble size, before the bubble coalescence occur. Finally, the digitized images were processed by using Image-J software to obtain the area of vesicle. The results were plotted as number density curves, forming 2D-bubble size distribution (BSD). Next, we determine the specific size of pheno- and matrix- bubbles based on the BSDs data (Fig. 2B).

Pheno-bubble and matrix-bubble number densities

Pheno-bubbles and matrix-bubbles were traced manually using mosaic and 500x image magnifications, respectively (Fig. 4S and 5S). Mosaic image magnification is used for PBND measurements in order to obtain the most representative PBND value from one grain image (grain size varies from 8.7 to 84.2 mm^2). 500x magnification image of the most homogeneous part that represent second nucleation was chosen for MBND measurement. Next, we manually digitize all pheno- and matrix- bubbles from each magnification. We corrected the bubble morphology in order to obtain the actual PBND and MBND values. PBND and MBND values were corrected by bulk- and matrix-bubble vesicularities as follows:

$$PBND\ (N_v) = (N_{ap}/d_p) * (1/1 - \varphi_{bv}) \quad (2)$$

$$MBND\ (N_v) = (N_{am}/d_m) * (1/1 - \varphi_{mv}) \quad (3)$$

where N_{ap} is number density per unit area of pheno-bubble, d_p is the average pheno-bubble size, φ_{bv} is bulk vesicularity, N_{am} is number density per unit area of matrix-bubble, and d_m is the average matrix-bubble size, φ_{mv} is groundmass or matrix vesicularity (vesicularity in 500x magnification images).

RESULTS

Componentry

We found that Maninjau ignimbrite consists of five main components as white pumice, grey pumice, banded pumice, lithic, and crystal. However, in this paper, we only report the detailed observation of white pumice. White pumice can be classified into transparent (TWP) and non-transparent (NTWP) type. TWP is typically glass-like, dominated in large vesicles, having irregular grain shape, and fragile. Conversely, NTWP is apparently non-glassy, lack of large vesicles, blocky in grain shape, and hard (Fig. 2A). Furthermore, each white pumice type can be sub-classified into three sub-classes based on the vesicle morphologies. Type I mainly includes spherical vesicles, type II is a combination of spherical and elongated vesicles, and type III mainly includes elongated vesicles (Fig. 2A). All sub-classifications of TWP distribute in the whole ignimbrite directions by following proportion: III (29 %) > II (19 %) > I (9 %). In contrast, most of NTWP correspond to type III (40 %). NTWP-I and II are absent in eastern deposits and their abundance are relatively rare (1 % and 2 %, respectively). In total, transparent type is the dominant phase of white pumice. Particularly, TWP exceeds 57 %, more than half portion of white pumice, while NTWP comprise 43 %.

Stratigraphy

Our stratigraphy data is basically in good agreement with Alloway et al. (2004). The lower ignimbrite is typically stratified (consists of many layers) and rich in gas-pipe structure, while the upper ignimbrite is typically massive (Fig. 1C). Based on componentry data, we found that the stratified facies is typically rich in TWP, free of grey and banded pumices, and dominantly lithic poor. Moreover, we were able to divide the massive facies into three units. The lower part of massive facies is typically rich in TWP, has no grey and banded pumices, and relatively poor in lithic content. Grey and banded pumices are firstly observed in middle part, accompanied with the increase of lithic content. In the upper part, NTWP is dominant in the white pumice phase, together with the abundant grey pumice, banded pumice, and lithic contents (Fig. 1C).

Definition of pheno-bubble and matrix-bubble

Qualitatively we can clearly recognize the large-sized bubbles in pyroclast considered as pheno-bubble, and the small-sized bubbles in groundmass with relatively narrow size variation considered as matrix-bubble. To be quantitative, we use BSDs data (Fig. 2B), which show that TWP contains smaller number of matrix-bubble and larger number of pheno-bubble compared with NTWP. Both white pumice types show bimodal distribution of BSDs, where the decay of exponential distribution is terminated at the beginning of second peak around 0.1 mm bubble diameter. Therefore, we define the boundary between pheno-bubble and matrix-bubble by the bubble diameter 0.1 mm.

Petrography, glass, and plagioclase compositions

Transparent and non-transparent pumices are typically crystal poor, having 3.2 and 3.4 % of average crystal content (vesicle-free) for TWP and NTWP, respectively. Phenocryst phase from both white pumice types are plagioclase, quartz, and small amounts of biotite, pyroxene, and Fe-Ti oxides (Fig. 2C). Transparent type has slightly larger average phenocryst size (0.31 mm^2) compared with non-transparent type (0.28 mm^2). Quartz phenocryst size vary from 0.05 to 7.5 mm^2, while plagioclase is smaller (0.07 to 3.9 mm^2), and other phenocrysts such as pyroxene, biotite, and oxide minerals are typically small (less than 0.05 mm^2). Although most of crystals grow as an individual crystal, some crystals form aggregates. Zoning textures (normal and oscillatory) are rarely found and only occur in plagioclase phenocrysts. Glass compositions of TWP and NTWP are indistinctive and regarded as high-silica rhyolitic melts (avg. 78.5 wt. % SiO_2). There is no remarkable difference of potassium, sodium, calcium, magnesium, silica, and anorthite contents between TWP and NTWP (Fig. 2D, 2E).

Density variations

TWP has slightly higher average bulk density value compared to NTWP (0.67 gr/cm^3 for TWP and average 0.61 gr/cm^3 for NTWP) (Fig. 3A). There is tendency for bulk density to increase from type I to III. Particularly, the average bulk density vary from 0.58, 0.63, and 0.80 gr/cm^3 for TWP, and 0.34, 0.68, 0.79 gr/cm^3 for NTWP with respective vesicle types.

Quantitative data of pheno- and matrix-bubbles

We found the negative correlation between pheno- and matrix-bubble fractions (Fig. 3B). Both TWP and NTWP also can be clearly distinguished based on the most dominant fraction between pheno- and matrix-bubbles. TWP is dominant in pheno-bubble, whereas NTWP is dominant in matrix-bubble (Fig. 3B). The average size of pheno-bubble and matrix-bubble in TWP are typically larger than NTWP. Note that volume fraction is positively correlated with average diameter, for both pheno- and matrix-bubbles (Fig. 3C, D). TWP has typically higher PBND than NTWP (Fig. 3F). TWP clearly show wider variation and smaller MBND value compared to NTWP, hence also yield in lower matrix-bubble volume fraction (Fig. 3G). Because matrix-bubble is negatively correlated with pheno-bubble, MBND will also result in negative correlation with size and volume fraction of pheno-bubble (Fig. 3H, J). Finally, we found two types of correlation between PBND and MBND: (1) nearly constant correlation for TWP, and (2) negative correlation for NTWP (Fig. 4).

DISCUSSION

Magmatic source of TWP and NTWP

Previous researchers have shown that Maninjau pumices have similar and homogeneous bulk and glass compositions (Leo et al. 1980, Alloway et al. 2004, de Maisonneuve et al. 2020). However, their data does not discriminate the types of white pumice for chemical analyses. Here, we confirmed that both TWP and NTWP at all deposit locations exhibit similar mineralogy characteristics and chemical compositions (Fig. 2C, D, E). This suggest that both white pumice types were originated from the same giant, highly evolved, and nearly aphyric-rhyolitic magma chamber, which erupted at the same time.

Formation of transparent and non-transparent white pumices

In Figure 3A, we can confirm quantitatively the negative correlation between pheno- and matrix-bubbles. This suggests that the existence of pheno-bubble can limits the supersaturation of matrix-bubble, in agreement with Toramaru (2014). We found that the boundary between TWP and NTWP is clearly defined by the volume fraction ratio of pheno- and matrix-bubbles (Fig. 3A). The boundary between TWP and NTWP is also clear in terms of number densities (Fig. 4).

Therefore, it can be simply inferred that; TWP originates from phenobubble-dominated magma, while NTWP dose from pheneobubble-poor magma.

Correlation of PBND and MBND: effects of magma decompression rate and pheno-bubble abundance

There are two important factors which are essentials for controlling the relationship between PBND and MBND. The first factor is the magma decompression rate (dP/dt). Toramaru (2006) have explained that MBND is proportional to 3/2 power of decompression rate. Therefore, we can expect that higher MBND value is generated by higher magma decompression rate, which might occur during the development of caldera. The best natural example of this condition is Santorini-Lower Pumice 182ka eruption (Simmons et al. 2017), whereas the MBNDs value increase from the early stage to the final stage. The second factor is be related to the distribution of pheno-bubbles in pre-eruptive magma chamber. It is known that the overgrowth of pheno-bubbles will increase the total surface area and depletion of gas in melt, hence diminishing the supersaturation (Toramaru 2014). Consequently, if the decompression rate is constant, second nucleation will be limited when the uprising magma contains such high number density of pheno-bubbles. Otherwise, second nucleation can effectively take place under the high PBND condition if the decompression rate is high enough (Toramaru 2014). The critical condition whether the second nucleation occurs or not under the certain decompression rate is simply represented by the similar values of PBND to MBND expected to take place by the decompression rate. In our case, the 10^{11} m^{-3} is an approximate critical value: the second nucleation start to take place when the decompression rate exceeds the enough value, about 0.1 MPa/s (Fig. 4).

In this study, we found that both conditions are observed in the Maninjau 52ka eruption. TWP is characterized by the high PBNDs value, suggesting that TWP magmas were extremely rich in pheno-bubble (Fig. 4). Interestingly, under the constantly high-PBND condition, TWP magmas were able to produce four different magnitudes of MBNDs value and its variation can be expressed by the function of time (Fig. 4). Particularly, as the eruption undergoes to the final stage, the MBND gradually increases. This suggests that, starting with a mild decompression, magma decompression rate increases towards the formation of caldera. On the other hand, NTWP show such monotonic steep decrease in PBNDs value together with the slight increase in MBNDs value. This condition likely corresponds to our second factor, that is, the decrease in pheno-bubble content (in nearly constant decompression rate) with time, leading to increase in supersaturation for matrix-bubble nucleation (Fig. 4). The transition from TWP-rich to NTWP-rich deposits from the lower until upper stratigraphic level (Fig. 1C) becomes an important evidence for the indication of pheno-bubble stratification in magma chamber. We suggest that the phenobubble-rich magmas were evacuated during the early stage under the initially mild and subsequent high decompression rate, producing TWP-rich ignimbrites (unit 1 – 3), and thus followed by the emplacement of phenobubble-poor magmas from the lower part that produces NTWP-rich ignimbrites (unit 4) (Fig. 1C).

REFERENCES CITED

Alloway, B.V., Pribadi, A., Westgate, J.A., Bird, M., Fifield, L.K., Hogg, A. & Smith, I. Correspondence between glass-FT and ^{14}C ages of silicic pyroclastic flow deposits sourced from Maninjau caldera, west-central Sumatra. *Earth Planet. Sci. Lett*. **227**, 121-133 (2004).

de Maisonneuve, C.B. & Bergal-Kuvikas, O. Timing, magnitude and geochemistry of major Southeast Asian volcanic eruptions: identifying tephrochronologic markers. *J. Quarter. Sci.*, **35 (1-2)**, 272-287 (2020).

Edmonds, M. & Woods, A.W. Exsolved volatiles in magma reservoirs: *J. Volcanol. Geotherm.*

Res. **368**, 13-30 (2018).

Harahap, B.H. & Abidin, Z.A. Petrology of lava from Maninjau lake, West Sumatra. *J. Geol. Res.* **16:6**, 359-370 (2006).

Leo, G.W., Hedge, C.E. & Marvin, R.F. Geochemistry, strontium isotope data, and potassium-argon ages of the andesite-rhyolite association in the Padang area, West Sumatra. *J. Volcanol. Geotherm. Res*. **7**, 139-156 (1980).

Purbo-Hadiwidjoyo, M.M., Sjachrudin, M.L. & Suparka, S. The volcano-tectonic history of the Maninjau caldera, Western Sumatra, Indonesia. *Geol. Mijnb.* **58**, 193-200 (1979).

Salisbury, M.J., Patton, J.R., Kent, A.J.R., Goldfinger, C., Djadjadihardja, Y. & Hanifa, U. Deep-sea ash layers reveal evidence for large, late Pleistocene, and Holocene explosive activity from Sumatra, Indonesia. *J. Volcanol. Geotherm. Res*. **231-232.**, 61-71 (2012).

Shea, T. Bubble nucleation in magmas: A dominantly heterogeneous process?. *J. Volcanol. Geotherm. Res*. **343**, 155-170 (2017).

Simmons, J.M., Carey, R.J., Cas, R.A.F. & Druitt, T.H. High magma decompression rates at the peak of a violent caldera-forming eruption (Lower Pumice 1 eruption, Santorini, Greece). *Bull. Volcanol*. **79:42** (2017).

Toramaru, A. BND (bubble number density) decompression rate meter for explosive volcanic eruptions. *J. Volcanol. Geotherm. Res.* **154**, 303-316 (2006).

Toramaru, A. On the second nucleation of bubbles in magmas under sudden decompression. *Earth Planet. Sci. Lett*. **404**, 190-199 (2014).

FIGURE CAPTIONS

Figure 1. (A) Distribution map of some major caldera forming eruptions in Sumatra Island, Indonesia, modified from Salisbury et al. (2012). Maninjau caldera is highlighted in req square.

(B) Sampling locations of this study (white star) and Alloway et al. (2004) (yellow star). (C) Simplified stratigraphic section of Maninjau 52ka eruption.

Figure 2. (A) Macroscopic and mosaic images for comparison TWP and NTWP with respect to its vesicle morphologies (B) 2D-BSDs data obtained from 200x magnification (C) Representative petrographic images of phenocrysts (D) Variations of K_2O, Na_2O, CaO, and MgO, with respect to SiO_2 in glass. (E) Variations of plagioclase anorthite core compositions

Figure 3. Correlation of some important textural parameters. See text for discussion.

Figure 4. PBND vs MBND diagram. Sphere sizes indicate different stratigraphic units.